

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: May 22, 1978

Project Title: Develop a Preliminary Design for a Solar Powered Irrigation System
Using a Concentrating Collector Concept

Project No: B-513

Project Director: Mr. J. D. Walton, Jr.

Sponsor: al Dir'iyyah Institute of Geneva, Switzerland; Arlington, VA 22209

Agreement Period: From 5/15/78 Until 8/15/78
(Preliminary Design Effort Period)

Type Agreement: Grant (and check no. 612, dated 5/12/78)

Amount: \$29,000

Reports Required: Informal Report; Final Report.

Sponsor Contact Person (s):

Technical Matters

Contractual Matters
(thru OCA)

Mr. Dennis W. Bakke, Director
Western Hemisphere Operations
al Dir'iyyah Institute of Geneva, Switzerland
1925 North Lynn Street, Suite 1140
Arlington, VA 22209

Defense Priority Rating: N/A

Assigned to: ASL/SEMTD (School/Laboratory)

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GEORGIA INSTITUTE OF TECHNOLOGY
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Date: November 10, 1978

Project Title: Develop a Preliminary Design for a Solar Powered Irrigation System
Using a Concentrating Collector Concept

Project No: B-513

Project Director: Mr. J. D. Walton, Jr.

Sponsor: al Dir'iyyah Institute of Geneva, Switzerland; Arlington, Va. 22209

Effective Termination Date: 8/15/78 (Reporting Period to 9/1/78)

Clearance of Accounting Charges: ---

Grant/Contract Closeout Actions Remaining:

- ☐ Final Invoice and Closing Documents
- ☐ Final Fiscal Report
- ☐ Final Report of Inventions
- ☐ Govt. Property Inventory & Related Certificate
- ☐ Classified Material Certificate
- ☒ Other Any unexpended portion of the grant shall be returned to the Sponsor.

Assigned to: Applied Sciences Laboratory/SEMTD (School/Laboratory)

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ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

June 19, 1978

Al Dir'Iyyah Institute of Geneva, Switzerland
1925 North Lynn Street, Suite 1140
Arlington, Virginia 22209

Attention: Mr. Dennis W. Bakke

Subject: Monthly Technical Letter Report No. 1, "Preliminary Design of an Experimental Solar Powered Water Pump," covering the Period May 15 through June 14, 1978 (Georgia Tech Project B-513).

Gentlemen:

The objectives of this program are:

- (1) To identify thermal engine components, including design characteristics and sources of supply, for steam or fluorocarbon engines to be used on solar powered water pumps in less developed countries,
- (2) To design suitable support hardware for a five-meter Scientific Atlanta paraboloid dish so that the dish can be used as a tracking solar collector.

The program is being conducted in anticipation of a major effort to develop and demonstrate solar powered water pumps in four less developed countries; this latter effort is expected to be funded by the United Nations Development Programme through the World Bank. The present program is designed to attack two areas where significant development will be required, and thus to permit a head start on the UNDP/World Bank program.

During the first month, several design concepts for the dish tracking mechanism have been generated, a list of steam engine manufacturers throughout the world have been compiled, several manufacturers have been contacted, and one possible source of fluorocarbon (Freon) engines has been found.

For the dish tracking mechanism, project personnel visited Scientific Atlanta, Incorporated and obtained detailed design information on the five-meter paraboloid dish and began design of support structures. It has been established that the dish must be capable of operation between north latitudes of 10 and 35 degrees, that it must operate in winds up to 30 miles per hour and must survive winds up to 100 miles per hour. It currently appears that a mechanical clockwork mechanism could be used to drive the dish about an

equatorial axis in order to accomplish the required tracking during a single day; Professor Giovanni Francia has successfully used such a mechanism at his solar steam pilot plant in Genoa. The seasonal declination adjustment will be accomplished by a manually operated jack screw mechanism since this adjustment must be made only one time each day. The tracking mechanism will require intermittent supervision throughout the day.

Two candidate dish support designs are shown in Figures 1 and 2. The daily rotational axis is represented by the shaft inclined at an angle of 35 degrees from the horizontal. (This shaft must be parallel to the earth's axis of rotation and would be more nearly parallel to the ground at lower latitudes.) In both figures, the dish is shown at one extreme of the declination adjustment and a dotted outline illustrates the other extreme declination position. The center of mass of the Scientific Atlanta dish is approximately at the vertex of the parabola, and the wind loads and turning forces would be minimized if the axis of rotation passed through this center of gravity. However, it is clear in both figures that mechanical interference will result if that design is used. Thus, it is necessary to support the dish at some position along the barrel-shaped structure extending downward from the center of the dish.

Another structural feature of the Scientific Atlanta dish is a system of radial struts extending from the base of the barrel to points near the edge of the dish. These serve as stiffeners to maintain the parabolic shape. Figure 1 illustrates a concept for supporting the dish at the lower end of the barrel, incorporating a concrete counterweight to minimize turning forces. Figure 2 illustrates a related concept in which the radial struts have been cut and attached to a new framework; this system reduces turning forces and wind loads but may cause imperfection in the dish shape. Design tradeoff studies are continuing.


Drag forces, lifting forces, and turning moments associated with winds have been calculated for the mounting scheme shown in Figure 2. This calculation was performed using two standard methods with similar resulting load values. For example, under the worst conditions of orientation, a wind of 100 miles per hour can exert a drag force of more than 8000 pounds on the five-meter dish in a horizontal direction. The structural components and frame must be sized with withstand this and other wind forces. Sizing of structural members in the framework is underway.

Approximately 20 potential sources of steam engines have been identified, although none of the available engines are entirely satisfactory for the proposed water pumping application. In general, the engines available are too large or too complex. A steam museum in north Georgia was visited and about four suitable engines were identified, but these are no longer in production; however, the possibility of reproducing these designs in less developed countries is being addressed.

Al Dir'Iyyah Institute
June 19, 1978
Page 3

During the second month of the program, quantitative sizing of the dish support hardware will be continued and a clockwork mechanism for tracking will be designed. Investigation of foreign sources for engines will be continued.

Respectfully submitted,

 J. D. Walton, Jr. // '
Project Director

jw

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JDW
PD

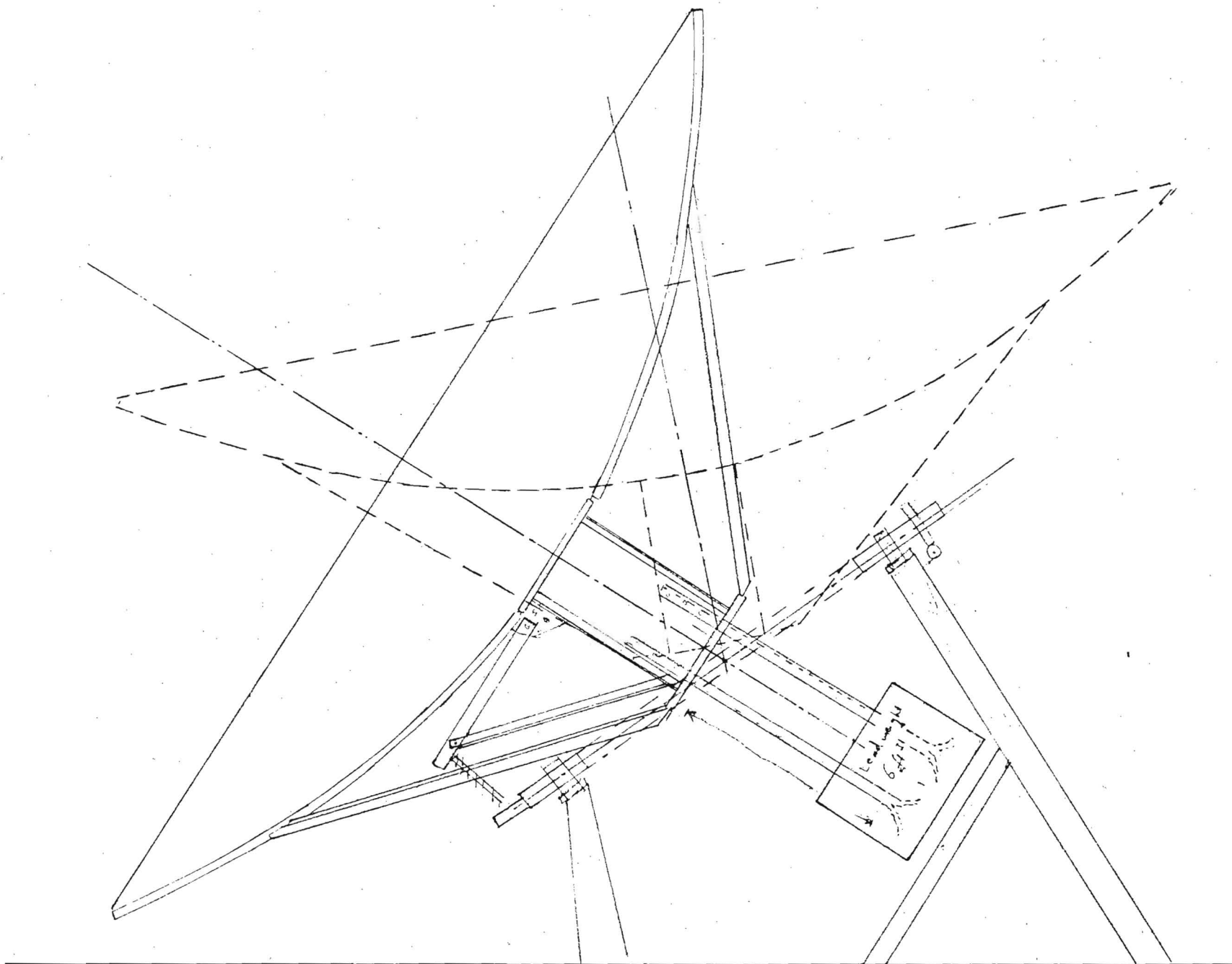


Figure 1. Parabolic Dish Mounting Concept without Cutting Radial Struts.

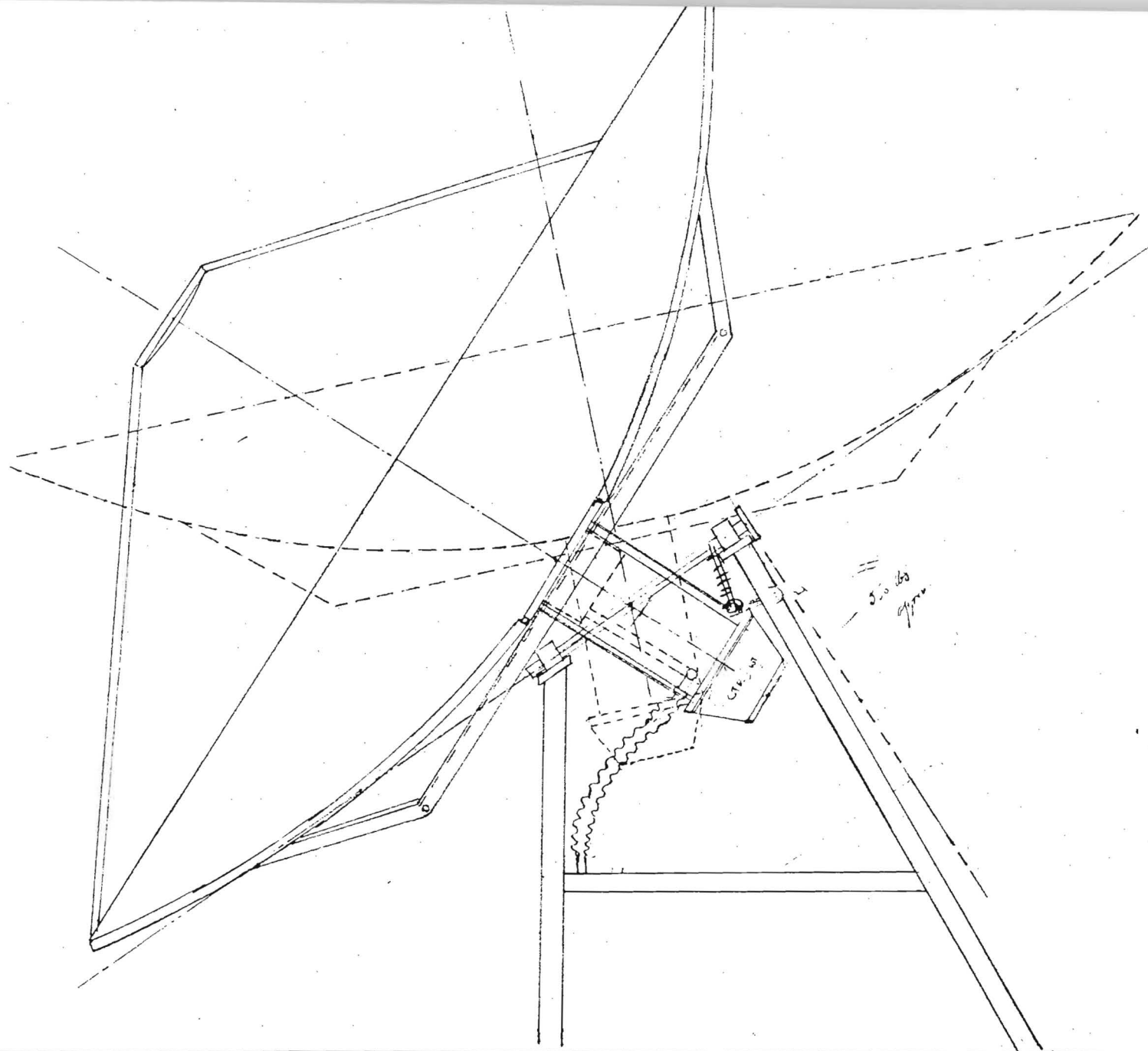


Figure 2. Parabolic Dish Mounting Concept with Radial Struts Removed and Supported on Ring.

**PRELIMINARY DESIGN FOR A
SOLAR POWERED IRRIGATION SYSTEM
USING
A CONCENTRATING COLLECTOR CONCEPT**

**FINAL TECHNICAL REPORT
May 15 through September 1, 1978**

**By
Steve H. Bomar, Jr.
Earl L. Meeks
Thomas B. Elfe
J. D. Walton, Jr.**

For

**AL DIR'IYYAH INSTITUTE
OF GENEVA, SWITZERLAND**

OCTOBER 1978

**GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Atlanta, Georgia 30332**

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Georgia Institute of Technology
Engineering Experiment Station
Atlanta, Georgia 30332

Georgia Tech Project B-513

Published October 1978

ABSTRACT

This report describes a preliminary design for a solar powered water pumping system intended for use in developing countries of the world. The design is based on the use of a concentrating collector concept, a Rankine power cycle employing Freon or steam as the working fluid, and a positive displacement pump driven by a dc motor or directly from the Rankine engine. The rationale leading to this system configuration was to minimize capital costs by achieving higher energy conversion efficiencies than are possible in more conventional solar pumping devices using flat-plate collectors.

Throughout the program, the requirements for operation in remote locations of the less developed countries were kept in mind. The needs for simplicity, reliability, and accommodation to the level of skills and facilities available in these countries have controlled the preliminary design.

PRELIMINARY DESIGN FOR A SOLAR POWERED IRRIGATION SYSTEM USING A CONCENTRATING COLLECTOR CONCEPT

I. INTRODUCTION

The results of a state of the art survey of solar powered irrigation pumps identified the need for water for irrigation and village use as one of the most serious problems facing the less developed countries of the world 1/. It also identified solar energy as the most practical means for providing the energy needed to power water pumps to the highly dispersed populations of the LDCs. Unfortunately, the high cost of such systems has prevented the widespread use of this energy resource. The report further pointed out that the high cost was associated primarily with the low collector temperatures and resulting low energy conversion efficiencies provided by the currently available solar powered pumping systems. The low conversion efficiencies must be offset by larger capital investments in equipment to achieve a given power output. Therefore, one of the recommendations of the report was the design and development of a simple solar powered pumping system which would operate with higher working fluid temperatures and increased conversion efficiencies, thereby reducing the cost of delivered energy to the point that solar pumping systems can be considered viable energy resources in the less developed countries of the world.

In May 1978, a grant was received from the Al Dir'Iyyah Institute to undertake the development of a preliminary design for a more efficient, high temperature solar thermal powered irrigation system with the following characteristics:

- o The size of the system should be in the range of 2 to 4 horsepower.
- o The cost of the system should be of the order of \$5,000/hp.
- o The technology employed should be compatible with manufacturing and maintenance facilities in the developing nations so that most components could be built and all repair functions could be accomplished locally.

References are identified by numbers in this format: 1/.

- o Operation of the system should be simple.
- o The reliability of the systems should be very high since trouble-free operation and ruggedness is a prerequisite to their gaining wide acceptance in the developing countries.

Primary effort on the program has been along two lines. The first was to choose a suitable collector and to design in detail a polar axis mounting structure (thus allowing one-axis tracking during the day for diurnal adjustment and once-a-day settings for solar declination adjustment). The second was to make a comprehensive survey of available Rankine cycle engines in the 1 to 5 horsepower range.

Secondary effort was devoted to the remaining elements of the system (pump, boiler, condenser, generator, etc). While these elements are certainly of no less importance than the collector and the prime mover, their selection and/or specification is straightfoward and does not represent a large engineering effort.

From the beginning of the preliminary design studies, it was apparent that certain experiments would be required - particularly with respect to prime movers - before some of the conclusions presented in this report could be confirmed. However, it is believed that the system described here stands an excellent chance of meeting the objectives of the program.

II. PURPOSE

The purpose of this study was to conduct a preliminary design for a solar powered irrigation system using a concentrating collector concept and a thermal engine power cycle. A design is described for supporting and tracking a solar collector using a polar axis geometry. Rankine cycle prime mover technology was reviewed to expedite selection of the optimum engine for converting thermal energy into shaft work suitable for driving a water pump or electric generator. Boiler designs are conceptualized in order to define the device needed to convert solar thermal energy into high pressure vapor. Other components of the system, such as pumps, feed lines, generators, and motors are described in order to complete the system concept.

Throughout the study, the requirement for operation in remote locations of the less developed countries was kept in mind. The needs for simplicity, reliability, and accommodation to the level of available skills and facilities have strongly influenced the preliminary design effort.

III. BACKGROUND

Since the oil embargo of 1973 world attention has turned to the problem of diminishing fossil fuel supplies and to the search for alternative energy resources. Among the renewable energy resources which are being considered, one of the most popular and perhaps the most promising is solar energy. The almost explosive growth of this technology since 1973 is evidenced by the fact the Federal (NSF-ERDA-DOE) budget for solar energy research and development increased from \$6 million in Fiscal Year 1973 to almost \$400 million for FY 1978 2/. Essentially all of these monies are directed toward solving solar energy problems associated with developed nations and are focused generally on a high level of technology, and a high standard of living.

Long before 1973 it was becoming apparent that the less developed countries (LDC's) would be facing energy problems quite different from those which would be faced by the developed countries in the 1970's. With a low technological base and immature economic development, the LDC's depend heavily upon man or animal power for mechanical energy and upon forest and agricultural products for thermal energy. Therefore, as these countries began the process of developing and as their population and standard of living began to increase, serious energy shortages developed. During this period a number of concerned organizations and individuals began to consider the problem of increased energy requirements for these countries and started experimenting with solar energy as a means of supplying their energy needs. These efforts generally have not been successful on a significant scale because of technical, economic, social or political reasons. However, they have served to identify and prioritize the most serious energy problems facing the LDC's. It is generally agreed that high among these is the need for pumping water to be used for irrigation and domestic purposes.

The great majority of people in the less developed countries cannot afford to purchase the conventional fuels used in the developed countries: petroleum and electricity. Also, the supply and distribution facilities for these fuels do not exist, even if the people could afford to buy them at world market prices. However, during the past 15 years it has been amply demonstrated that solar energy can provide the energy necessary to pump

water for irrigation and domestic use. Further, because of the distributed nature of solar energy, it is readily available to the widely dispersed village population of most of the less developed countries of the world. In many places subsurface or river water is also available if some means for pumping it could be provided. Thus, the challenge is to develop solar pumping devices which are both technically and economically suitable to meet the needs of rural people in less developed countries.

Some of the existing solar pumping systems are technically acceptable but far too expensive for widespread adoption. The high capital cost per unit power output is a consequence of low power conversion efficiency; the conversion efficiency is limited by the low working fluid temperatures which can be obtained with flat plate solar collectors. One way to circumvent this dilemma is to employ concentrating solar collectors, which give higher working fluid temperatures and higher conversion efficiencies, thereby reducing the collector area needed for a given power output. Since the collector represents by far the largest item of cost in a solar system and for a given collector design the cost is approximately proportional to area, a substantial reduction in collector area will have a large impact on the system cost. Therefore, development of a solar pumping system with high conversion efficiency, using a concentrating collector, should result in substantially lower capital cost per unit power output. However, solar energy devices based on this logic have, up to now, employed high technology unsuitable for the circumstances existing in less developed countries.

This preliminary design study was intended to define a water pumping system which gained the higher conversion efficiencies permitted by concentrating collectors, but avoided the error of incorporating technical sophistication too elaborate for use in the intended market. For example, paraboloid dish solar concentrators have been built with electronically operated azimuth-elevation tracking schemes. The approach in this study was to use a simple, mechanically operated polar axis tracking scheme. The present direction of most solar power conversion research is toward turbines or specially designed reciprocating engines. The approach in this study was to use 19th century steam technology or a mass-produced Freon engine adapted from the refrigeration industry. This search for simple concepts, which can

be built inexpensively and understood by unsophisticated people, characterized the entire program.

It is most urgent that the technical feasibility of a concentrating solar water pumping concept be evaluated as soon as possible in order that valid comparisons with existing flat plate pumping systems can be made. The innovative concepts involved in concentrating solar water pumps are the tracking systems and the power conversion systems. Accordingly, a high-technology paraboloid dish has been chosen for the collecting surface because it is readily available on the commercial market; it is recognized that this item might eventually be replaced by a segmented surface of glass mirrors if local manufacturing capabilities dictate such a change. However, the validity of the tracking and power conversion concepts would not be altered by the adoption of a different collector surface, if that change ultimately became necessary.

IV. TECHNICAL DISCUSSION

A. System Concepts

The finalized and presently recommended solar thermal powered water pumping system concept is shown in Figure 1. Solar energy is collected and concentrated by a paraboloid dish with a sub-reflector that redirects the energy back into an absorber in the antenna hub. The absorber is also the boiler for a Freon Rankine-cycle engine. The Freon engine drives a dc generator which in turn powers a dc motor for pumping the irrigation water. Part of the water pumped will be used for cooling the Freon condenser and part of the engine power will be used to drive a boiler feed pump.

This system concept has several noteworthy features: (1) It is independent of all external power sources (except the sun) and could be used in any part of the world that has sufficient insolation. (2) High production and high reliability components are utilized wherever possible to provide maximum service at lowest cost. (3) The major working parts are packaged in a small compact unit, much like a window air conditioner, that can be easily removed from the antenna hub for service or replacement. (4) Both deep and shallow water sources can be serviced with the same unit by selection of the proper water pump. (5) All parts of the system could be adequately serviced or repaired by a competent auto or refrigeration service mechanic.

B. Details of Major Components

1. Collector

a. Paraboloid Concentrator. The concentrator consists of a 5 meter diameter paraboloid antenna, covered with aluminum reflecting sheet, having a reflectivity of 0.80. This will provide approximately 15 kW of thermal power. Based on the field experience of Acurex Aerotherm and Omnium-G, the preliminary design will utilize Alcoa's lighting sheet designated as Coilzak with class MI protective finish.

The particular antenna chosen is manufactured by Scientific Atlanta and is fabricated by bolting together 24 panels, each of which is a triangular segment of the paraboloid. The antenna dish, modified for this application,

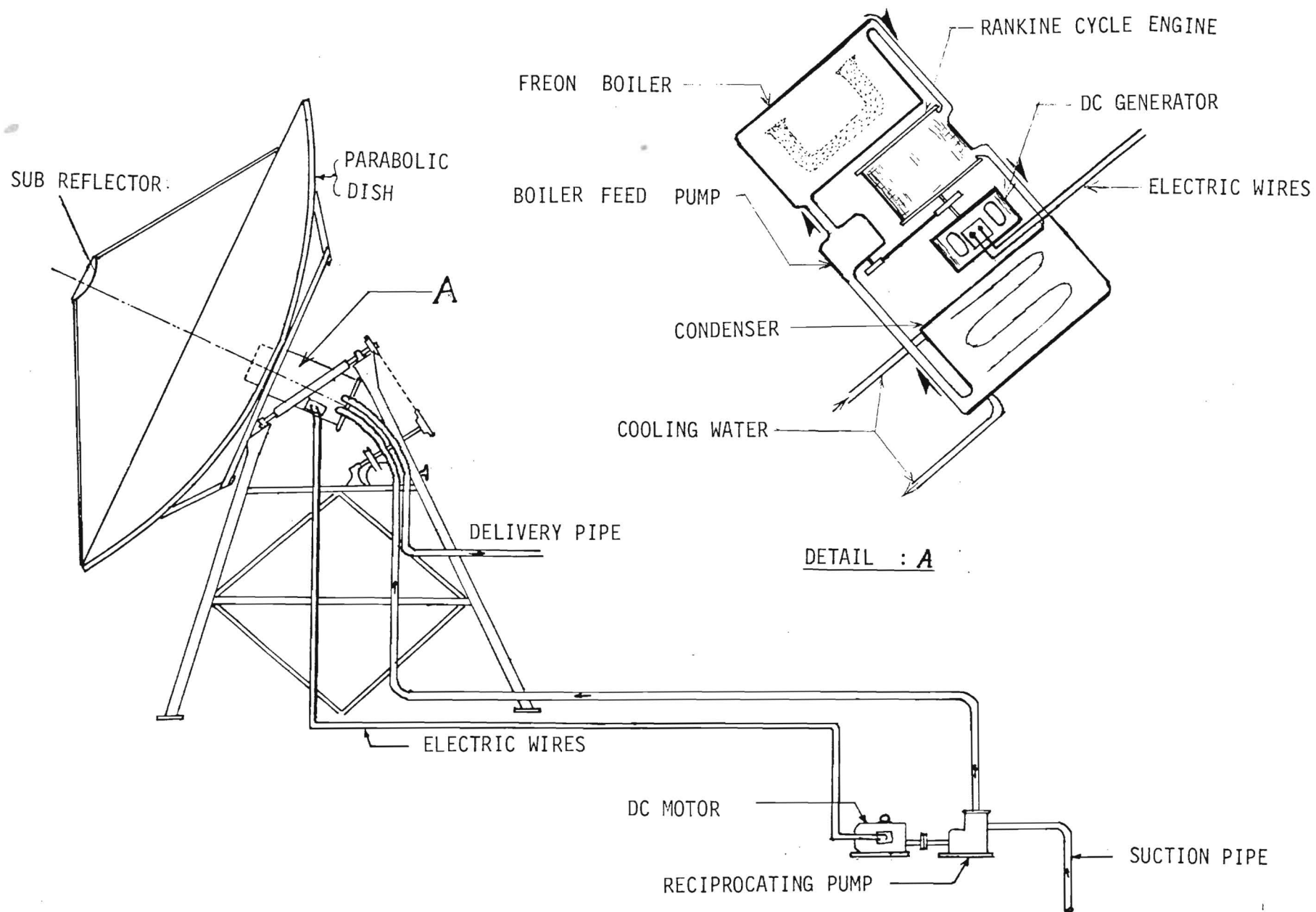


Figure 1. System Concept Outline.

is shown in Figure 2. While these panels are by no means simple to manufacture, it is a technology which could be developed in India, the Philippines, or Africa. Details of the collector are given in Table I. An alternative concentrator might be more easily fabricated in LCD's from a welded metal framework to which glass mirror segments are attached. A 25 square meter paraboloid dish concentrator has been constructed using this technique in Rawalpindi, Pakistan at a reported total materials cost of less than \$1,000 3/. A tracking 100 square meter point focus concentrator of similar design has been constructed in France 4/. However, such designs require substantial development and should be considered on a local basis after the principle of the concentrating solar water pumping concept has been proven using the available paraboloid dish proposed here. Also, these designs must be adapted to an equatorial mount in order to simplify tracking.

In this connection, the support pedestal for the concentrating collector using the Scientific Atlanta antenna was completely redesigned to accommodate an equatorial axis. Since the original antenna was designed for satellite communication, the pedestal was designed for azimuth/elevation tracking with rather limited adjustment. Figures 3 and 4 are photographs of the antenna in its present configuration. In order to simplify tracking, either automatic or manual, a polar axis mount was selected so that during a given day, tracking could be accomplished by simple rotation of the collector about its axis. A worm and worm gear train is provided for this rotation. A simple screw jack adjusts the axis tilt for seasonal changes. Figures 5 and 6 show the polar-axis mounted collector and indicate seasonal and hourly extremes.

In order for the equatorial axis tracking scheme to work successfully, the axis of daily rotation for the paraboloid dish must be parallel to the earth's axis of rotation. This requires that the dish's axis of rotation be accurately aligned in a north-south plane and tilted to an angle above the horizontal equal to the latitude angle of the installation site. The required alignment can be established using standard land surveying techniques and instruments, and once established, will never vary for that particular site. A concrete foundation for the antenna pedestal has been designed and a template will be provided for setting mounting studs in the concrete; the template will have north-south indices for alignment of the studs.

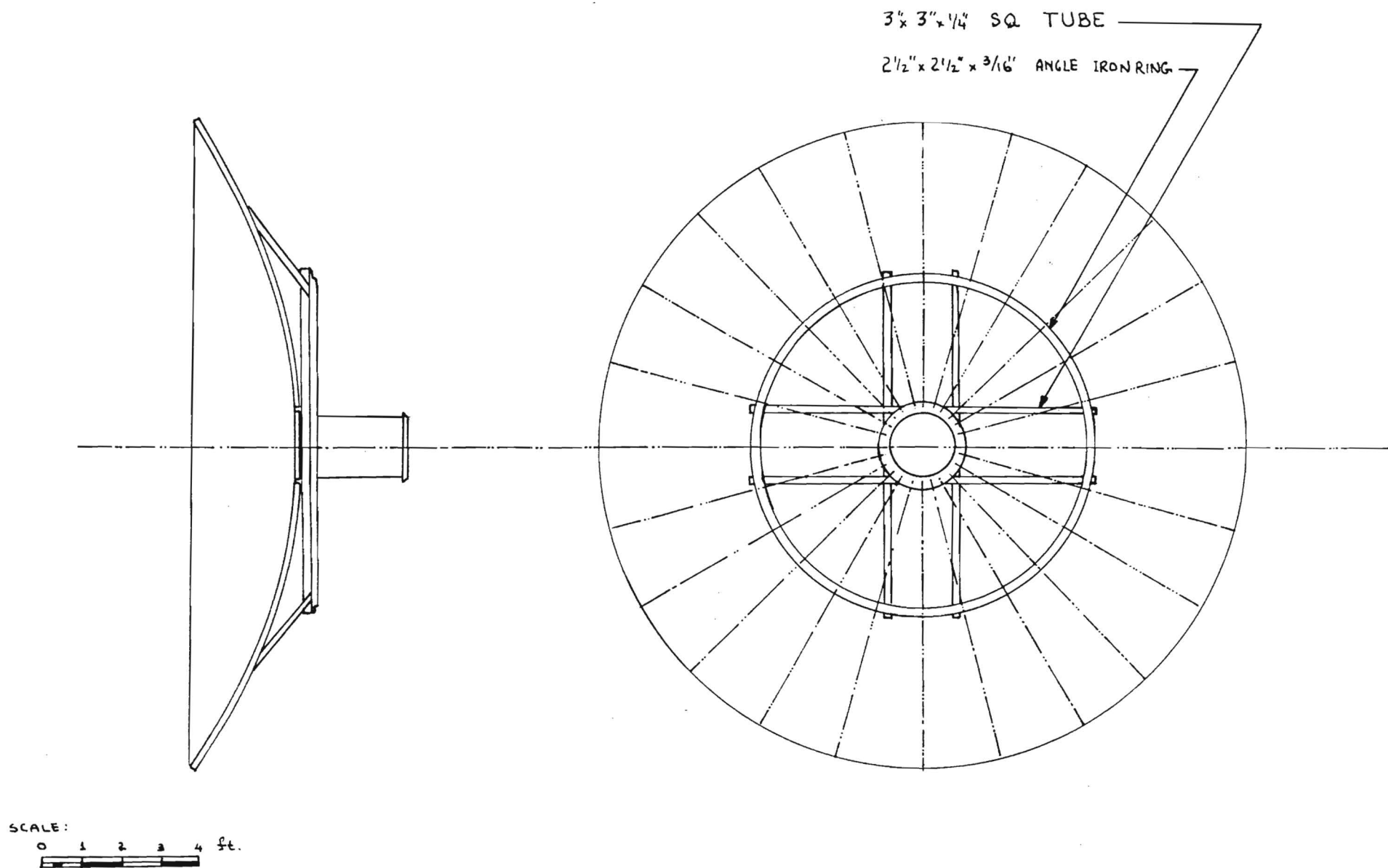


Figure 2. 5 Meter Antenna Dish.

TABLE I
COLLECTOR PARAMETERS

<u>Reflector:</u>	
Shape	: Parabolic dish
Diameter	: 5 meters (16½ ft)
Focal Length	: 1.9 meters (6¼ ft)
Source	: Scientific Atlanta
<u>Mount:</u>	
Type	: Polar axis
E.W. Movement	: 180 ⁰
N.S. Declination	: 47 ⁰ (i.e., $\pm 23\frac{1}{2}$ ⁰ to polar axis)
Pivot Point	: 0.38 meters (1¼ ft) from vertex
Wind Load	: 44.7 meters/sec (100 mph) (any position)
Operational Wind Load	: 15.6 meters/sec (35 mph)
Support Structure	: Steel
Base	: Concrete
Gear Assembly	: 2 worm gears (Ratio: 1.48 each)

The structural steel antenna pedestal has been designed to survive winds up to 45 m/s (100 mph) and to operate in winds up to 16 m/s (35 mph). Standard radar antenna design techniques were used to establish the magnitudes and directions of stresses on the pedestal as functions of paraboloid dish orientation, then structural members were sized to withstand "worse case" loads.

Since the collector's rotational axis is approximately 38 cm (15 in.) behind the center of gravity, a 270 kg (600 lb) counterweight will be provided to balance the collector. This, coupled with the mechanical advantage of the worm gear, reduces the torque required for tracking to less than 11 Nm (15 ft-lbs).

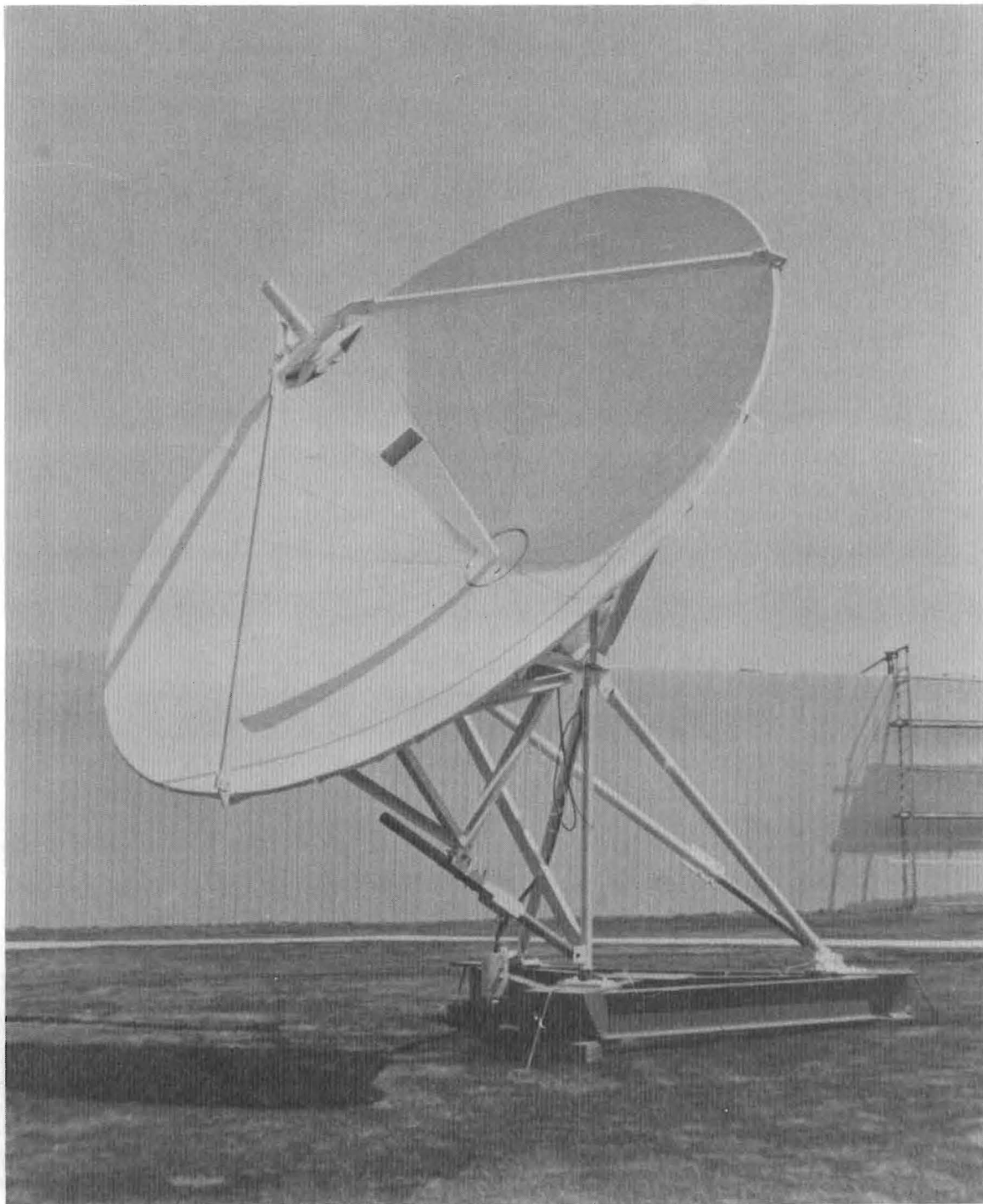


Figure 3. Satellite Communications Antenna - Front.

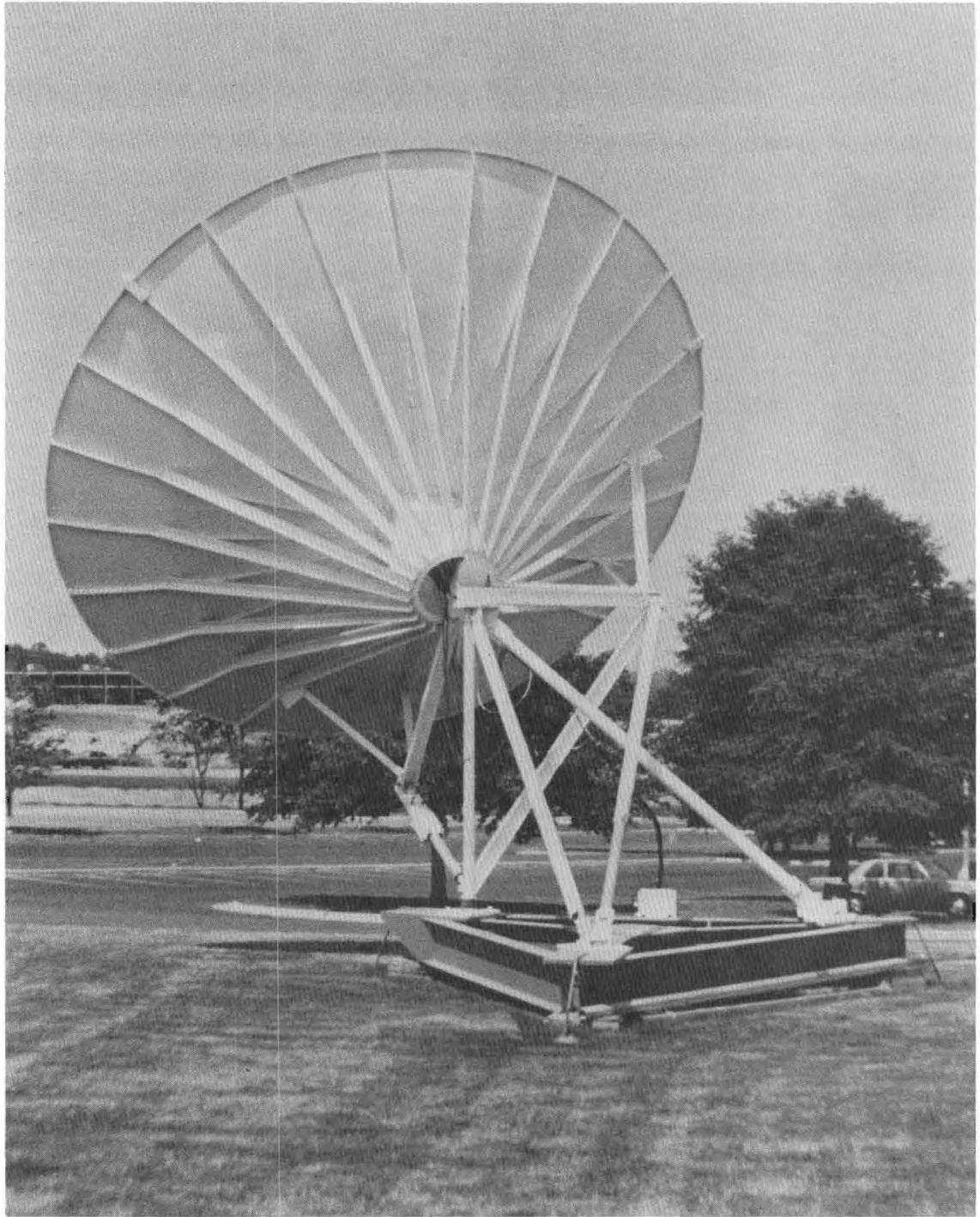
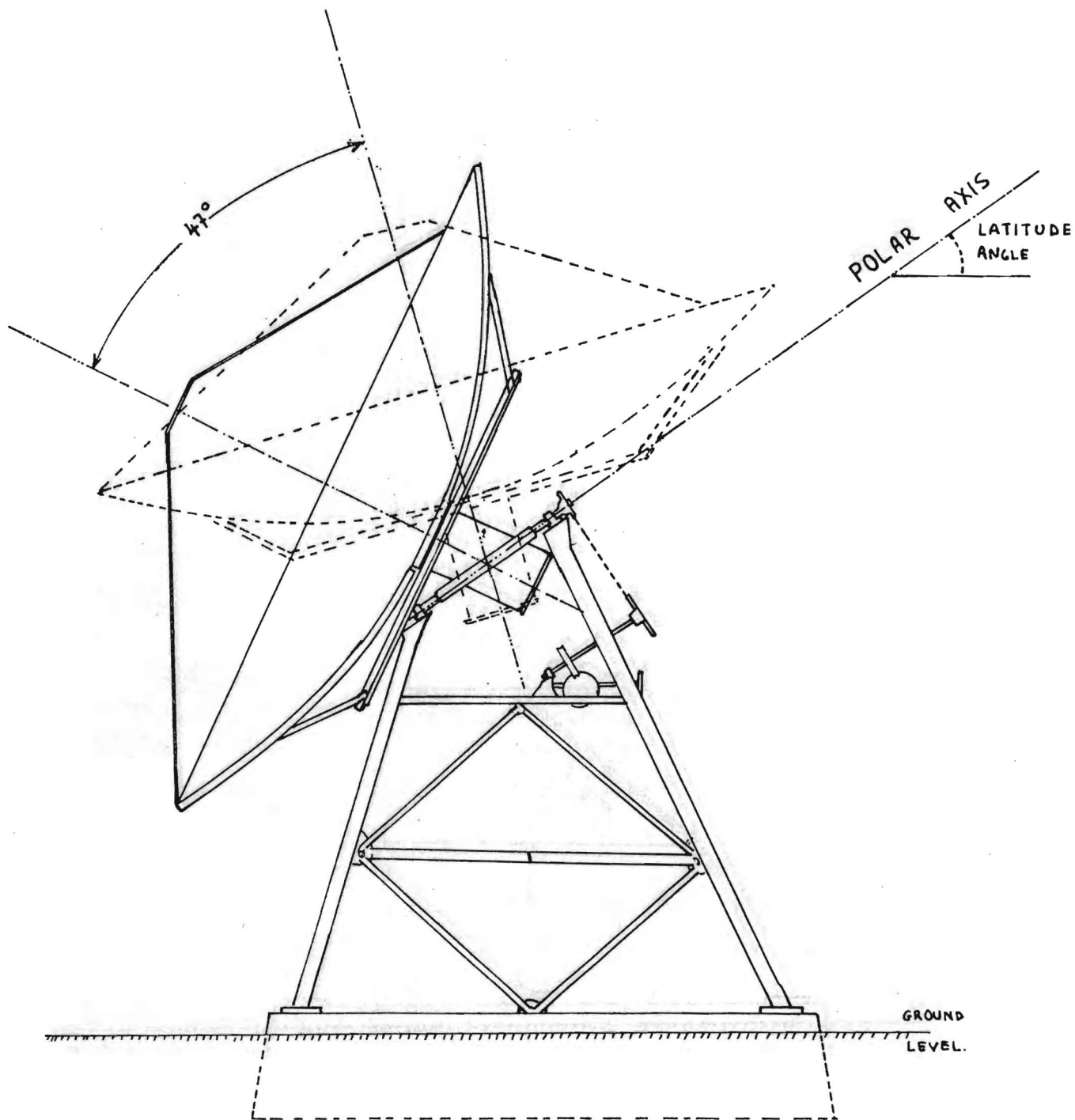


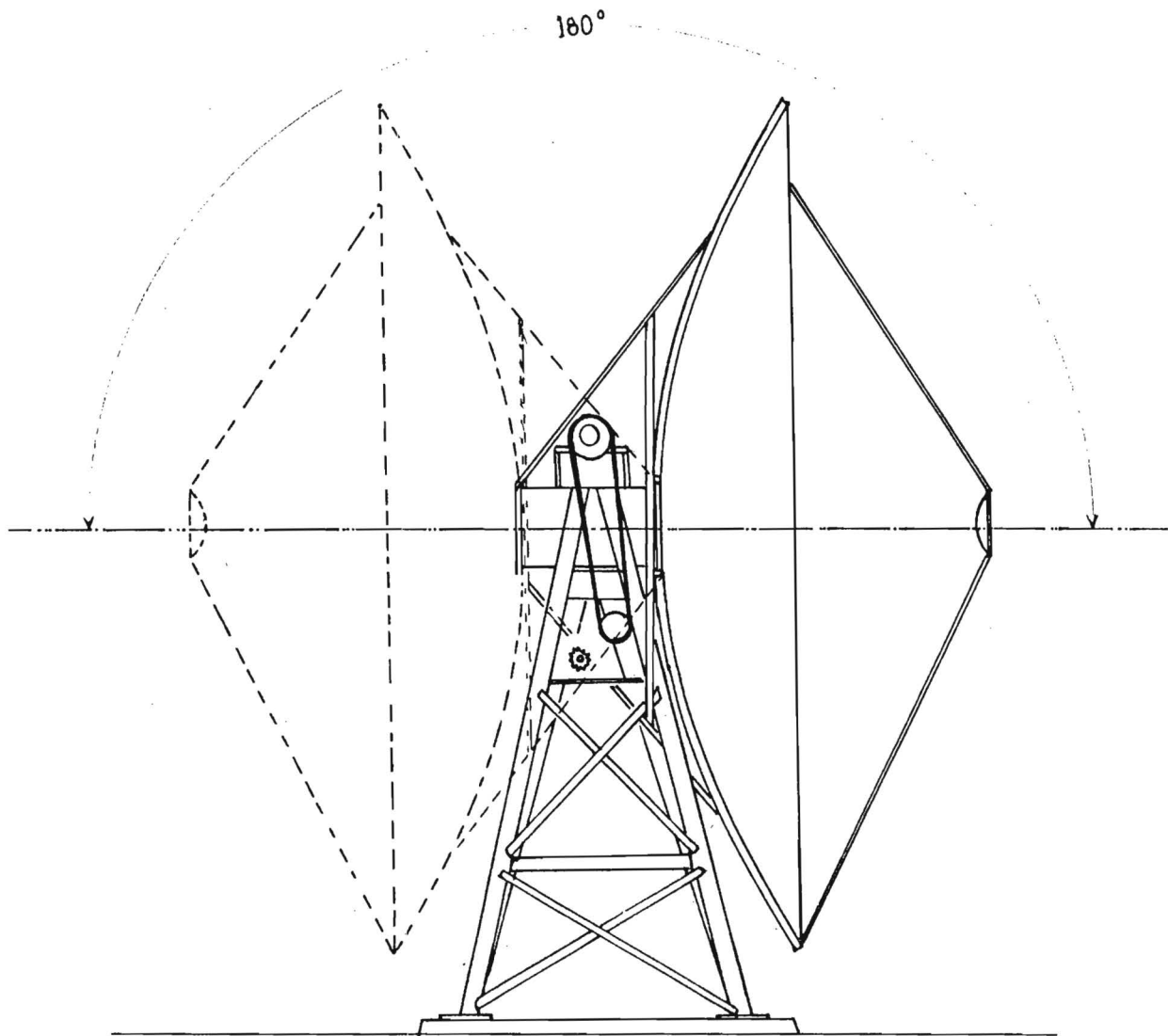
Figure 4. Satellite Communications Antenna - Back.



SCALE:

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Figure 5. Seasonal Collector Adjustment.



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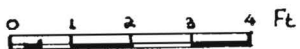


Figure 6. Hourly Collector Adjustment.

b. Sub-Reflector. The communications antenna manufactured by Scientific Atlanta is a Cassegrainian design employing a secondary or sub-reflector which intercepts the RF energy from the antenna horn (extending from the hub of the dish) and reflects it to the paraboloid dish surface from which it is reflected into space as essentially parallel radiation. Assuming reciprocity using a specularly reflective surface, incoming solar radiation should be reflected from the paraboloid dish to the sub-reflector and then into the hub of dish. This arrangement would permit the receiver, boiler, heat engine, condenser and dc generator to be located in the hub where the weight would add counterbalance and the power conversion apparatus would be relatively accessible for servicing or replacement. However, the success of this concept depends upon obtaining a very highly reflective coating (about 95 percent) for the sub-reflector which would permit it to function without active cooling. If such a coating cannot be found or if it proves impractical to keep such a reflective surface clean, then the receiver and thermal-electrical conversion package would be relocated at the focal point of the paraboloid. In this case the receiver package would be supported on a structure similar to that supporting the sub-reflector (see Figure 3). The Omnium-G system places the receiver (boiler) at the focus of the paraboloid reflector and the remaining equipment on the ground. However, in the present system, it is anticipated that the receiver, Freon heat engine, condenser and dc generator would be sufficiently light that they could be placed at the focus if necessary. This is possible only if the Freon heat engine, described later, is found to be suitable for this application. Otherwise, the high pressure, heated fluid must be transported from the boiler receiver along the support rods to the heat engine. Obviously the most attractive design would be the lightweight system in which all components can be co-located as a packaged unit.

2. Tracking

Since the collector mount is polar axis, as opposed to azimuth/elevation, the hourly tracking could be done manually with a single control. However, since the overall performance of the system depends on accurate

tracking, we consider that the diligence of the operator could be a questionable link in the system.

The automatic tracking system which will be incorporated is fairly simple. It consists of a weight attached to a cable which is wound around a drum on a shaft and is coupled to the worm gear train by chain and sprockets. A clock escapement mechanism controls the falling of the weight, thereby supplying the hourly tracking motion.

One escapement mechanism which appears especially suitable is the Grimthorpe Gravity Escapement illustrated in Figure 7 5/. This device uses no complex escapement wheel, whose tooth spacings and angles are usually critical for successful operation. Instead, it employs two gravity pallets which control the periodic release of the mechanism and impart a driving pulse to the pendulum with each half-cycle of the pendulum swing. As the pendulum moves to the right past its center position, as shown in Figure 7, it raises the right pellet, unlocks the right escapement stop, and permits the locking wheel to rotate to the next position where it is stopped by the left escapement stop. Rotation of the locking wheel causes a lifting pin to lift the pallet still further, effectively storing potential energy in the pallet. Near the right end of the pendulum's swing, the pallet imparts this potential energy into the pendulum as kinetic energy, thereby insuring that the pendulum will complete another half-cycle. The locking wheel is connected by gears or a drive cable to the dish rotation mechanism. The weight which powers the dish rotation also furnishes the energy required for the locking wheel rotation; the escapement mechanism serves as a speed regulator for the daily dish movement, in exact analogy to its function in a clock gear train. The Grimthorpe mechanism has been used for more than 100 years in London's "Big Ben" and other large tower clocks, so that its design is well proven in timing applications.

Clock escapement mechanisms are also available in kit form at modest cost. It may be advisable to compare the Grimthorpe mechanism and several kits to determine which best fits the application. The principal considerations are that the relatively large weight does not unduly impair the timing accuracy or introduce excessive wear and that the escapement can operate relatively

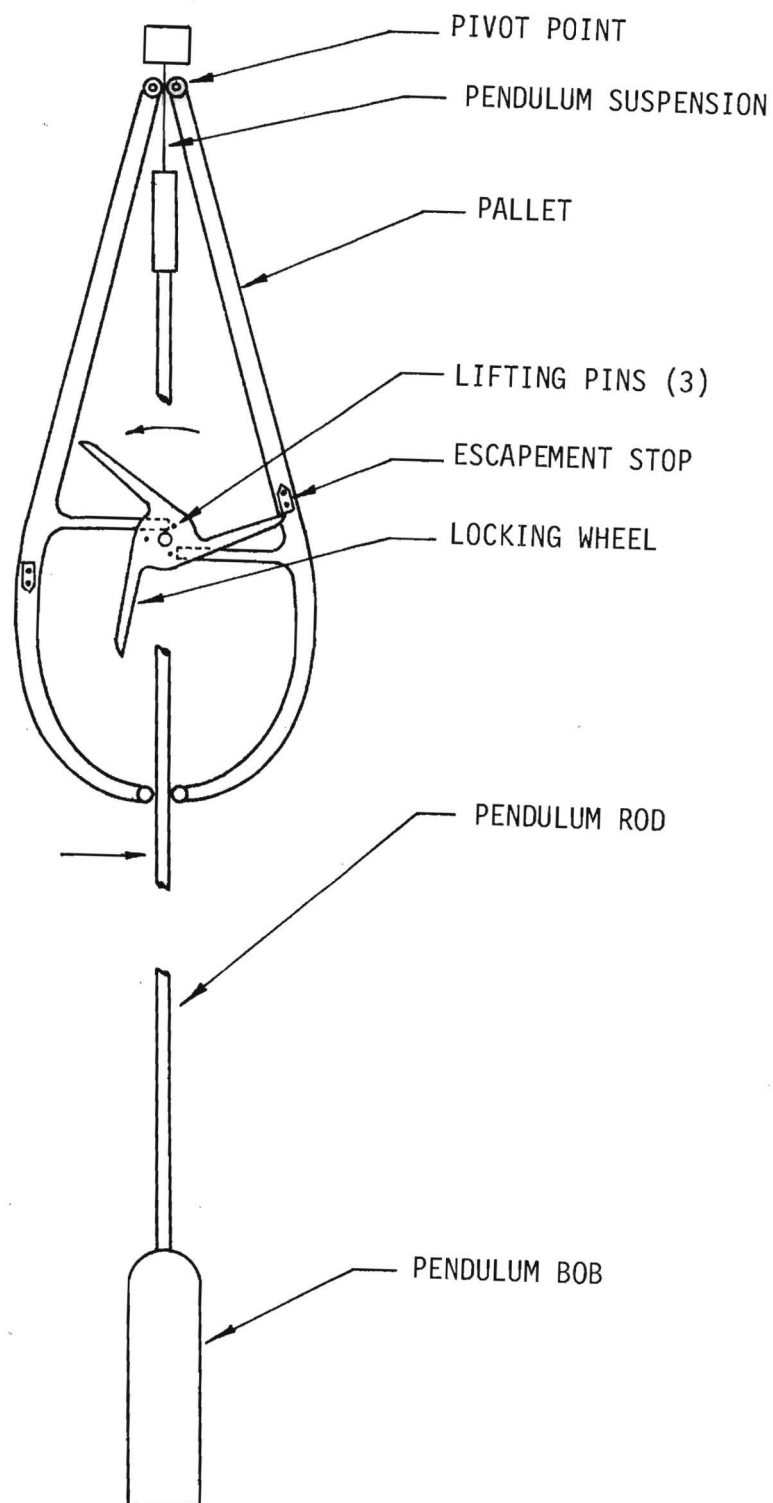


Figure 7. Grimthorpe's Gravity Escapement.

maintenance-free in the anticipated operating environment. An old tower clock mechanism with added driving weights was used by Francia to power his original solar steam pilot plant at Genoa, Italy; this system included 130 tracking heliostats focused on a 100 kW steam boiler suspended above the mirrors 6/. The Francia pilot plant has recently been converted to use an electric drive system, but the tower clock drive worked satisfactorily for more than 15 years. Francia's experience demonstrates the feasibility of mechanical timing devices for powering solar tracking equipment.

3. Absorber Boiler (A-B)

As pointed out previously, the present concept utilizes a sub-reflector located at the focal point of the paraboloid dish to focus the energy into an absorber cavity located in the antenna hub. The same absorber unit is also the boiler for the Rankine cycle fluid. The usual location of the absorber-boiler (A-B) is at the focal point since the use of a secondary reflector causes a loss of incident power. For the 5-meter dish, this power loss would be about 750 W or less (assuming a reflectivity of 0.95 can be obtained) and several advantages are gained by accepting this loss. The A-B, engine, generator, condenser, and boiler feed pump can be designed into a compact single unit as shown in Figure 1. The experimental development and testing of the system, as well as field maintenance, will be much easier if this unit can be quickly disconnected and slipped out of the hub for service or exchange. There is less shadowing because the sub-reflector is smaller than the boiler and because no insulated boiler feed and vapor return lines are needed at the redirector. The lines for circulating the working fluid are all in the hub and can be short and well insulated. Calculations show that gains from reduced shadowing and decreased thermal losses are almost equal to the 750 W reflection loss.

A cross section drawing of the conceptual design of the A-B is shown in Figure 8. The base design heat engine will utilize Freon R114 with an inlet temperature of 127°C (260°F) and a pressure of 2320 kPa (337 psia). About 15 kW (51,000 Btu/hr) will be the maximum A-B input flux (with direct solar radiation of 1000 W/m^2) and this flux will of course fluctuate with the

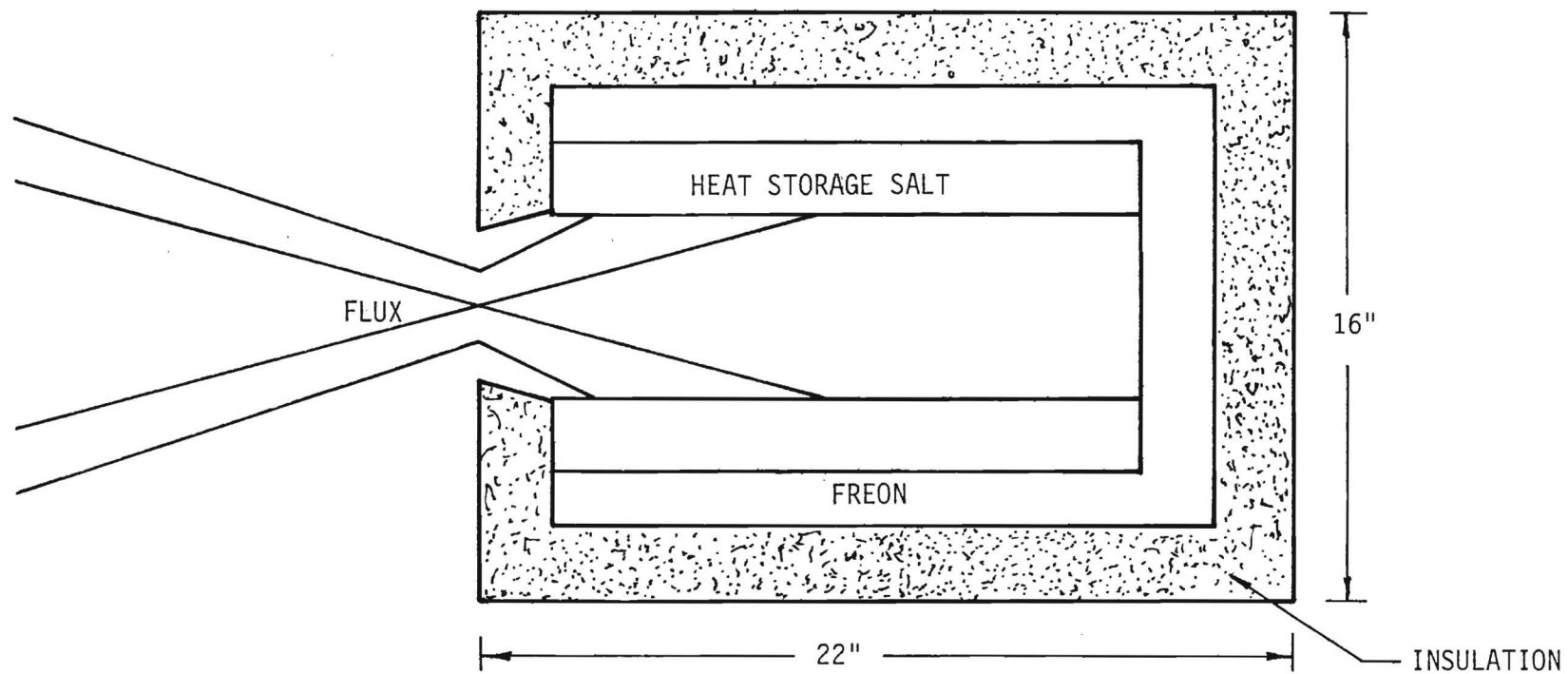


Figure 8. A Cross Section Drawing of the Absorber-Boiler.

passage of clouds. In order to smooth out some of the short duration cloud cover fluctuations, a thermal storage salt is included in the absorber design. A eutectic mixture of 66 wt percent LiNO_3 and 34 wt percent KNO_3 melts at 129°C (264°F) and will store 66.7 cal/gm in heat of fusion. About 14 liters (0.5 ft^3) will store 10 minutes of input heat energy which will be released during short term cloud cover to maintain boiler operation. Molten salts have good heat transfer coefficients which result in efficient heat transfer but the thermal conductivity of the frozen salt limits the charge and discharge rate. Additional design is necessary to optimize the charge and discharge rate of the thermal storage in the A-B. Since only a small amount of salt is needed, thin sections of salt storage with large surface areas can be used. If latent heat of fusion cannot meet the rate requirements, then sensible heat storage will be used with a commercial heat transfer salt of the NaNO_3 , NaNO_2 , KNO_3 type (trade names HITEC or Partherm 290).

4. Prime Mover

The York Automotive Division of Borg-Warner has in production a vane type rotary Freon compressor for use in automobile air conditioners. This unit appears to have excellent possibilities for use as the Freon expander (prime mover) for the prototype model. A drawing of the compressor is shown in Figure 9. It is about 20 cm (8 in.) long, 13 cm (5 in.) in diameter, and weighs 6.8 kg (15 lbs). The price of a single compressor unit with electric clutch is \$85.00. The electric clutch is not a necessary part of the proposed system and could be omitted if the compressors were purchased in quantity. Thus, the price of the expander in quantities of 1000 is expected to be of the order of \$50.00.

Although such a compressor should function as an expander, no data are available on its operation in this mode. Therefore, it will be necessary to conduct a series of experimental tests in order to evaluate its performance as an expander. A 3 hp cooling water refrigeration unit is being modified for the evaluation tests, a York compressor has been ordered and testing of the compressor as an expander will proceed in the near future. Other Freon expander units which are available as completely sealed units have been

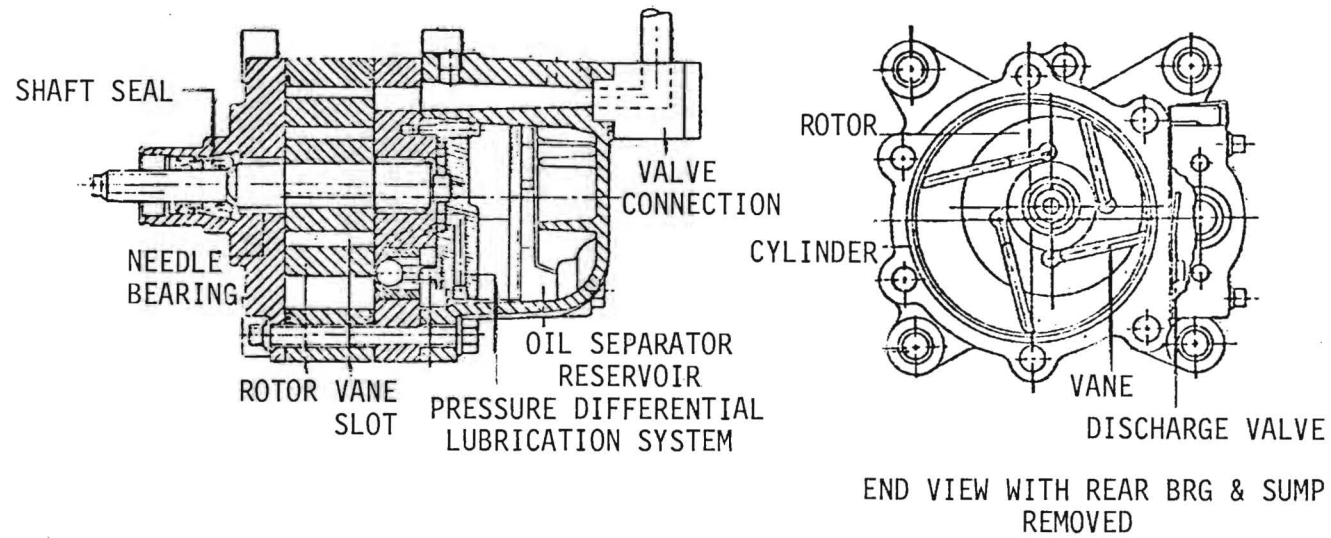


Figure 9. York Multivane Rotary Compressor.

suggested by Acurex Aerotherm. Such units have only two pipe connectors for entrance and exit of the working fluid and will be considered in the event the York compressor does not perform satisfactorily as an expander.

5. Pump

The pump will be a piston-type lift pump driven by a dc electric motor. It will be located above ground if the well is sufficiently shallow to operate in the "suction" mode; otherwise, the piston and valve assembly will be submerged and the motor and crank assembly will be located at ground level.

The pump will be powered by a series-wound dc motor driven by an automobile-type alternator powered by the Freon expander. This combination has the advantage that it will pump a reduced quantity of water under adverse operating conditions, rather than stalling. Also, the efficiency of both the pump and motor are relatively independent of speed, which will vary with the applied voltage. In essence, the system will generate as much power as the input solar conditions permit and pump as much water as that amount of power permits.

6. Other Components

Tentative selections of standard hardware items have been made for other system components such as the boiler feed pump and the condensing heat exchanger. Manual starting of the Freon expander and feed pump may be necessary; this will be done with a hand crank mechanism after the absorber-boiler has approached the operating temperature of about 127°C (260°F). Further specification of system components is dependent on the results of prime mover tests in which the operating characteristics of the York automotive compressor will be evaluated in the "expansion engine" mode. However, it is clear that the major components, with the obvious exception of the dish support, tracking mechanism, and absorber-boiler, can be purchased as commercial hardware items.

A Bill of Material for the components necessary to construct a solar water pumping system according to the preliminary design described herein is given as an appendix to this report.

C. Alternative Solutions

1. Collector

Several collector schemes were evaluated before the Scientific Atlanta 5-meter antenna was chosen. Other parabolic antennas were either too expensive, too large or were manufactured by techniques which would be difficult to implement in developing nations.

The decision to make the collector from the 5 meter paraboloid as opposed to a parabolic trough was a narrow one. The parabolic trough could be cast ferro-cement. Once the molds are made, the casting operation could easily be carried out locally. The other advantage of the parabolic trough is that the support structure would be less complicated and they represent state of the art technology in concentrating collectors.

These factors were outweighed by the higher concentration of the paraboloid and the potentially higher efficiency and lower overall system cost. Therefore, the decision was made to proceed with the point focus dish collector with the trough collector as a back-up should unexpected problems develop with the dish. Finally, in order to optimize the trough system it would be necessary to use a glass envelope to surround the absorber tube and the potential hazard of glass breakage could pose a serious service and maintenance problem.

2. Tracking

Although clock escapement mechanisms may be considered delicate, their operation is straightforward, and in LDC's it would be expected that it would be easier to get a clock escapement repaired than some more sophisticated system. Other methods which were considered included a timing mechanism which operates on the principle of a water clock, and a photocell system.

The water-timer consists of two tanks. The large tank has a float, which is attached to a counterweight by a chain which passes over a sprocket. Water drains from the large tank to the small tank through a float valve. A second float in the small tank operates the float valve to maintain a constant water height in the small tank. Water then drains from the small tank at a

constant rate through an orifice, resulting in a constant rate of change in the level of the large tank. This system was discarded because it is sensitive to wind velocity variations. The depth that the float in the large tank sinks into the water depends on wind velocity and direction.

The photocell system consisted of two photo cells, a balanced transistor amplifier, and a small electric motor. The principle of operation depends upon two photocells so aligned and mounted that equal light impinges on both cells when paraboloid is aimed at the sun. This results in equal bias being applied to the amplifiers, resulting in zero net output voltage to the motor. In the event of an unbalance, the motor runs in one direction or the other until balance is achieved. A thermistor bridge could be substituted for the photocells. In any event, this approach was discarded as being an unfamiliar technology in the typical developing country. Also, since the output power of the system is only of the order of 2 or 3 hp, the parasitic load imposed by the tracking motor could significantly reduce the net power output.

3. Absorber-Boiler

Some discussion has been presented above comparing the advantages and disadvantages of placing the A-B in the antenna hub or in front of the antenna at the focal point. These two cases cover the primary possibilities for the dish collector, but additional options must be considered for the trough collector.

The absorber for the trough collector must be as long as the collector and can no longer serve as the boiler. In Figure 10 the absorber and boiler are separate and a heat transfer fluid and circulating pump are used to heat the Freon for the Rankine cycle engine. If steam is used, the brief cloud cover storage could be in extra boiler water. The latent heat in 200 pounds of water would store 10 minutes of operating heat but the boiler pressure would drop off slowly from 150 to 80 psia. Alternately, the storage could again be in the heat of fusion of an eutectic salt mixture encapsulated and added to the Freon or water boiler.

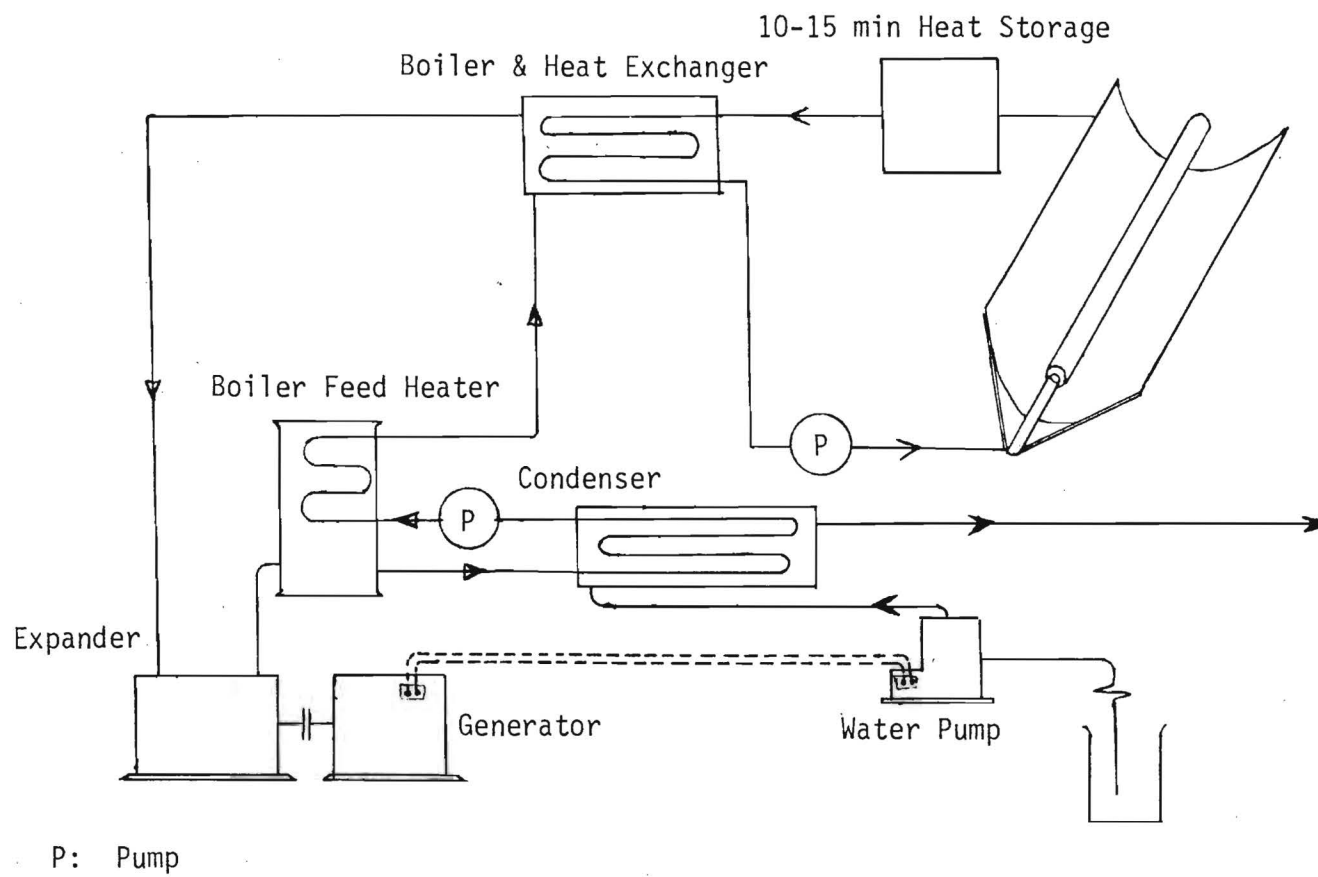


Figure 10. Flow Schematic with Parabolic Trough Collector.

4. Prime Mover

For maximum overall system efficiency the prime mover must be selected with great care and steam is an attractive alternative to Freon for a Rankine cycle fluid. Calculations of the thermal efficiency given in Table II show that the steam cycle is theoretically more efficient than Freon. In practice, however, the reverse may actually be the case. Table II also gives a comparison of dry saturated steam at 360⁰ F and superheated steam at 460⁰ F. There is no theoretical advantage in using superheated steam, but in practice the improvement in thermal efficiencies of both reciprocating and turbine engines with superheat are well known. The primary advantage gained through the use of superheat is in the reduction of losses due to condensation on the cylinder walls. Water on the cylinder wall evaporates during the exhaust stroke at the expense of heat in the cylinder wall. As a result, the walls are considerably cooler than the entering steam and initial condensation occurs to repeat the cycle. Superheated steam can give up the whole of its superheat without condensation and a greater amount of work can be done per pound of steam flow. Consideration of the proposed power cycle shown on the pressure-enthalpy diagram for R-114 (Figure 11) shows that the Freon will remain superheated for an adiabatic expansion from initial conditions of 260⁰ F and 337 psia. Thus, initial condensation is not expected to be a problem with the Freon expander and it may be more efficient in practice than a steam engine even though steam has the theoretical advantage.

Two additional points need to be considered from the data given in Table II. First, the volume of fluid flow per Btu for R-114 is 1/20th that of steam and half that of R-11. It follows that the displacement (physical size) of a R-114 expander is only 1/20th that of the equivalent steam expander and this is of prime importance in the design of a compact unit. Second, the boiler feed pump work for R-114 is twice that of R-11 and, therefore, the choice of which Freon would serve best is not clearcut. Experimental evaluations need to be made in order that the best tradeoffs can be made.

From the tracking parabolic dish, 15 kW can be expected as the maximum thermal energy to the boiler. If the boiler is 70 percent efficient, 10.5 kW or 35,800 Btu/hr will be potentially available as steam. Depending on pressure

TABLE II
COMPARISON OF RANKINE CYCLE FLUIDS

	Inlet Temp.	Inlet Pressure	Inlet Enthalpy	Outlet Enthalpy Ideal Case	80% of Ideal Enthalpy Change	Enthalpy of Boiler Feed	Efficiency	Engine Displacement per Btu	Boiler Feed Work 3→3'
Type	$T_1^{\circ}\text{F}$	P_1 psia	h_1 Btu/lb	h_{2s} Btu/lb	$0.8(\Delta h)_s$ Btu/lb	h_3 Btu/lb	$\eta = \frac{0.8(\Delta h)_s}{h_1 - h_3}$	$\frac{v_2}{0.8(\Delta h)_s}$ Btu/ft ³	Feed Pump work Btu/lb
R-11	260	202	120	104	12.8	29.5	14%	0.14	0.367
R-114	260	337	104	91	10.2	31.8	19%	0.068	0.61
H ₂ O	360	150	1195	877	254	68	23%	1.31	0.45
H ₂ O	460	150	1253	918	268	68	23%	1.31	0.45

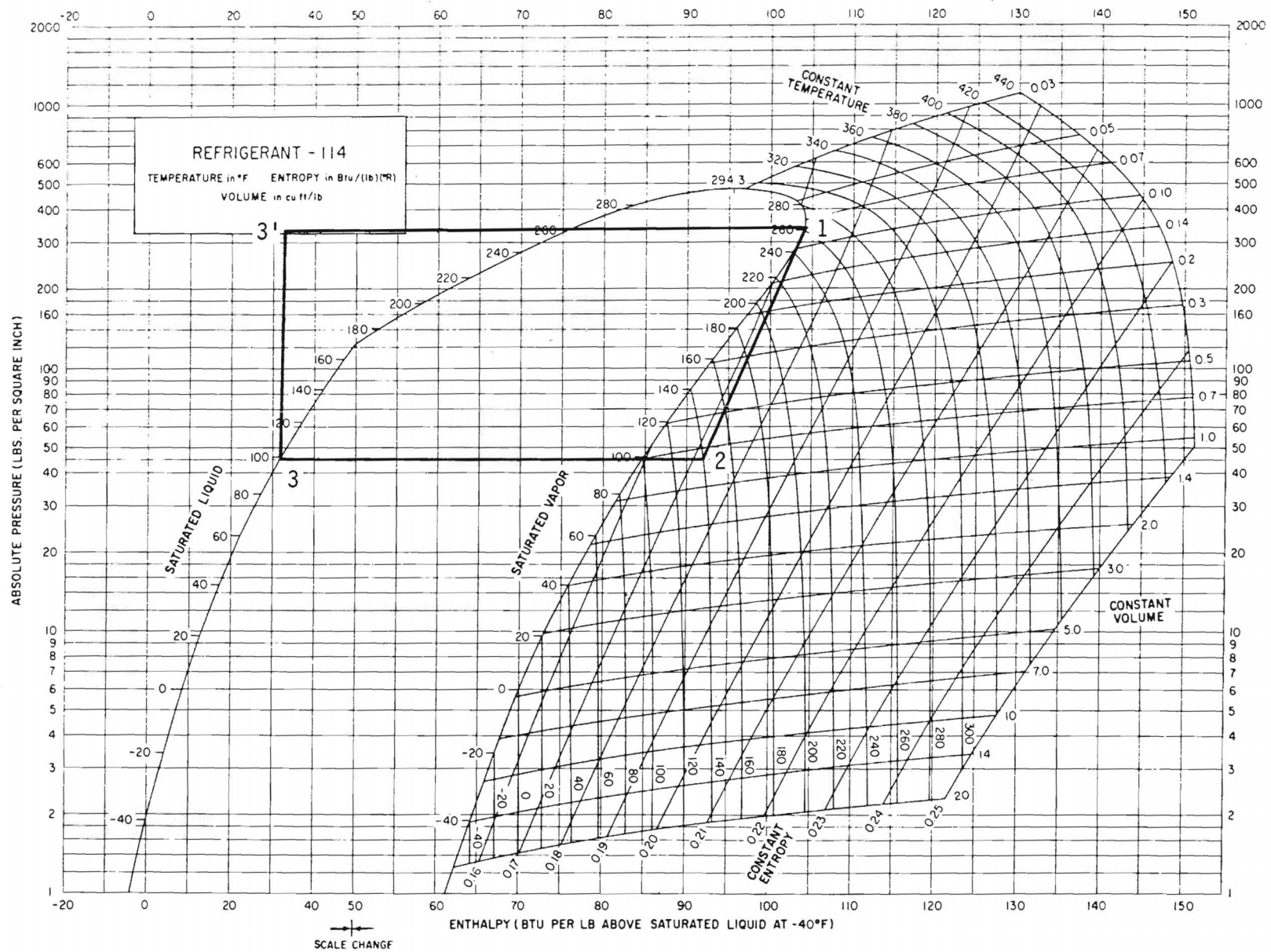


Figure 11. Pressure Enthalpy Diagram R-114.

and superheat conditions this amounts to about 30 pounds of steam generated per hour. The simplest kind of steam engine (simple, slide valve, non-condensing) uses about 35 lb/hp-hr 7/, whereas the most efficient reciprocating engines (uniflow, poppet-valve, condensing) approach 10 lb/hp-hr 8/. The low steam rate is reported only for large (200 hp) engines and can not be expected from an engine in the 2 hp range. With the use of superheat and efficient engine design it may be possible to hold the steam rate below 15 lb/hp-hr and thus obtain a 2 hp output.

An extensive search for steam engine suppliers produced the list given in Table III, but the only engines available in the 2 hp range are model engines such as Stuart-Turner or Clarkson. It is much better to operate a small engine at full capacity rather than a larger engine at partial capacity. For example, the steam rate of a simple slide valve engine operating non-condensing goes to over 50 lb/hp-hr at one-quarter capacity. The more efficient compound or poppet-valve engines have a flatter steam rate curve which affords more design latitude; but in any case, the choice of available engines for this application is restricted to the model engines. If the model engines prove to be inadequate, modifications will have to be made to improve efficiency or a new engine will have to be designed and built.

5. Pump

At the beginning of the program, a centrifugal pump was considered; preferably, a suction pump but clearly a submersible pump if the well depth is too great for a suction pump. Since it was decided to drive the pump with an electric motor, the advantage of the suction pump over the submersible is only one of ease of maintenance, rather than mechanical power transmission.

After consulting several pump manufacturers, it became evident that the loss of efficiency at reduced operating speed posed a serious problem with centrifugal pumps. It was therefore concluded that a lift, or piston pump would be superior, in that such a pump operates with fairly constant efficiency at all speeds.

A jet pump was also considered. The jet pump has the advantage that it could be located anywhere (even in the antenna hub) so that the problem of

TABLE III
STEAM ENGINE SUPPLIERS

Company	Type of Engine
Skinner Engine Co. 343 W. 12th St. Erie, PA	Single, duplex 8-180 hp 300 hp Uniflow
Spilling Consult AG Sonnenwes 4 CH5610 Wohlen-Switzerland	40-300 hp modular
Soule Steam Feed Works P. O. Box 5757 Meridian, MS	16 hp reversible twin for sawmill feed
Semple Engine Co. Box 6805 St. Louis, MO 63144	5 & 10 hp simple & compound marine launch engines
Roy Ferrier 5737 Venice Boulevard Los Angeles, CA 90019	Makes engines to order
O'Connor Engineering Labs 100 Kalmus Drive Costa Mesa, CA 92626	Makes engines to order has 17-30 hp Uniflow 5 hp slide valve
Thermo Electron Corp. 74 West St. Waltham, MA 02154	Makes engines to order (Freon or steam)
Solar Energy Systems Columbus Road Burlington, NJ 08016	Twin cylinder piston valve
H. Clarkson & Son 53/57 Lagerthorp York, GB YO37XB	2 hp compound twin (model maker)
Stuart-Turner LTD Henley-on-Thames Oxon, RG, 92AD, G.B.	2 hp duplex slide valve (model maker)

mechanical linkage between the prime mover and the pump becomes insignificant. The efficiency of jet pumps is appreciably poorer than either centrifugal pumps or lift pumps, however, so it appeared that the dc generator-motor chain would represent a smaller sacrifice in efficiency than would the jet pump.

6. System Configuration Tradeoffs

A functional block diagram of the solar powered water pumping system selected during this preliminary design study is shown in Figure 12. Under the present concept, the absorber-boiler, expansion engine, condenser, feed pump and dc generator would be housed in the central hub of the paraboloid dish. The pump would be run by electric power and its output water would be passed through the condenser before discharge to the user. Several alternatives to this configuration are possible, depending on the results of experiments which have been mentioned and the results of further economic tradeoffs:

- (1) If the absorber-boiler, engine, condenser, feed pump and generator were placed at the focus of the dish because the sub-reflector concept proved unworkable, the mass imbalance would be aggravated, maintenance would be less convenient, and the water would have to be pumped to the focus for the condenser. It might be preferable in this case to place only the absorber-boiler at the focus and other components on the ground.
- (2) If the absorber-boiler were placed at the focus and other components on the ground, insulating high-pressure piping would be required for Freon vapor and liquid lines to the boiler. Maintenance and water piping would be simplified. It might be advisable in this case to drive the pump directly from the expansion engine, eliminating the capital cost of the generator and electric motor, but also eliminating the possibility of using electricity for purposes other than pumping water.
- (3) To avoid the separation of the boiler and other components, it would be possible to install a primary heat transfer loop using a hydrocarbon oil fluid to move energy from the absorber, at the focus of

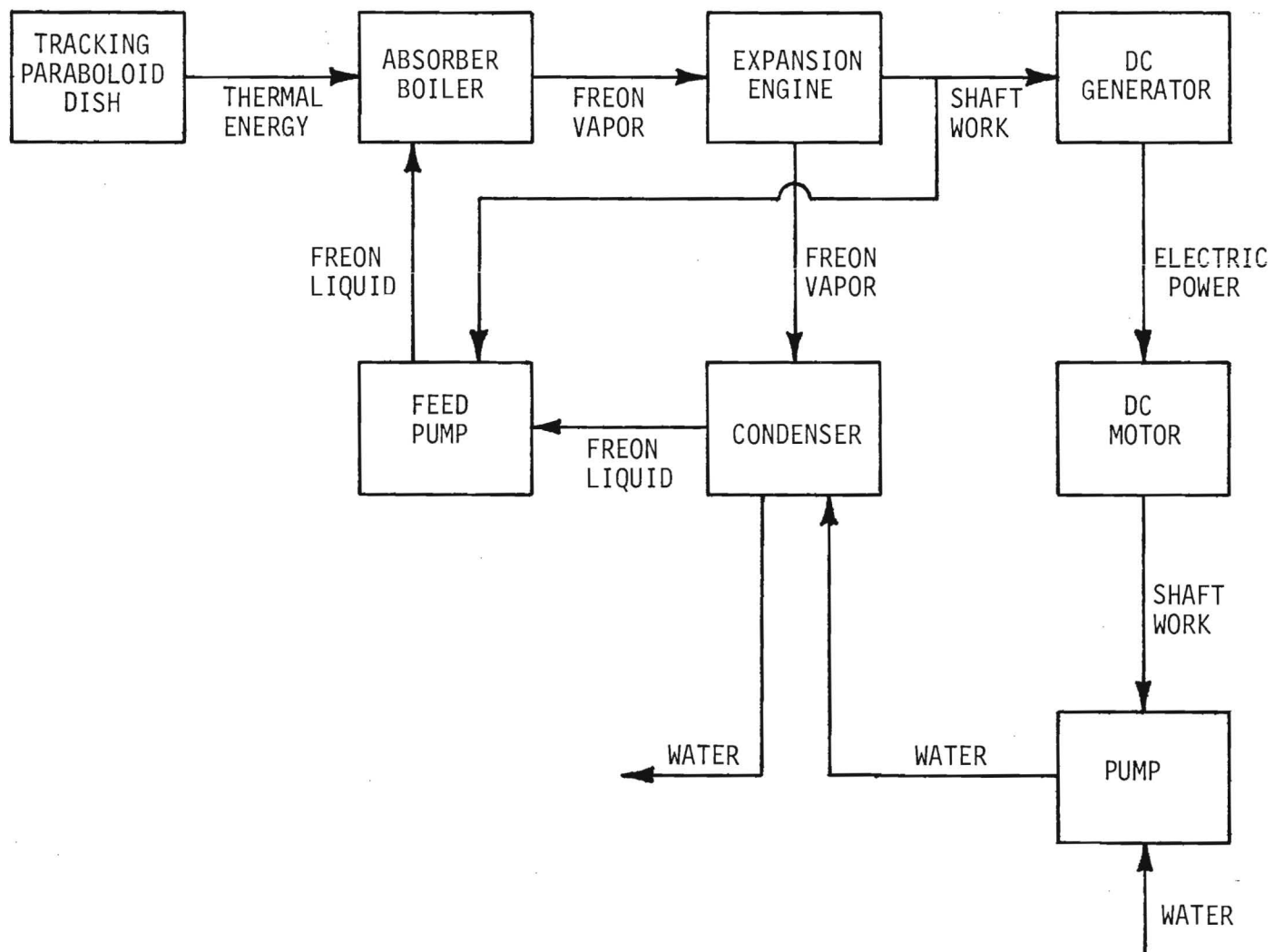


Figure 12. Functional Block Diagram for Solar Water Pumping System.

the dish, to the Freon boiler on the ground. This eliminates high-pressure equipment on the dish but requires the use of an additional fluid, an additional fluid transfer pump, and a surge tank.

- (4) If the Freon engine concepts prove to be unworkable, a water-steam working fluid could be adopted. Two suitable sources of model steam engines have been identified, although the probable lifetime of the engines under continuous operation is unknown. The technology for handling feedwater and boilers at moderate steam temperatures and pressures is well understood.

It is clear that a large number of technical tradeoffs are possible, as the operating characteristics and economics of the pumping system are revealed by experiments. However, the basic concept of a solar pump run by concentrating collectors promises to overcome the most serious barrier to widespread use of solar pumping systems, high capital cost.

V. CONCLUSIONS

The system described in Section IV.A. appears to do the most complete job of meeting the requirements of this program - namely, to provide a 2-3 hp solar thermal powered irrigation system at moderate cost which could be reproduced, for the most part, in developing countries. Several experimental tests remain to be performed, and unexpected results would doubtless alter the design of the system. However, at the present time, this system appears to be the one which could most probably meet the design objectives.

To reiterate, the system consists of:

- o A concentrating collector. The collector will be made from a 5 meter paraboloidal satellite communications antenna. The mount will be polar axis. Hourly tracking will be provided by a shaft, turned by weights and controlled by a clock escapement.
- o A Freon boiler. The boiler will heat Freon R-114 to a temperature of 260⁰ F. Pressure will be approximately 337 psia. A eutectic salt mixture will provide heat storage so that the system will continue operating for 10 minutes of cloud cover.
- o A rotary Rankine cycle engine. Originally designed as a compressor for an automatic air conditioning system, this engine provides efficient conversion to rotary motion in a compact, low cost, light weight package.
- o A water cooled condenser. The condenser will be a small shell and tube heat exchanger cooled by pumped water.
- o A dc generator. To avoid an inefficient (and possibly unreliable) mechanical transmission system from the engine to the pump, a dc generator will be driven by the rotary engine and will deliver power to a dc pump motor.
- o A dc pump motor. This motor will run at a speed depending on applied voltage to pump as much water as the available solar power permits.

- o A lift, or piston pump. This pump will pump water at relatively constant efficiency over a wide range of speed.
- o Total materials and components cost about \$9,000.

The results of this preliminary design indicate that the proposed system, although untested, offers the best possibility for providing the required irrigation pumping power at a potential production cost of \$5,000 horsepower.

APPENDIX

BILL OF MATERIAL FOR SOLAR WATER PUMPING SYSTEM

TABLE IV. BILL OF MATERIAL

S/NO	PART	DESCRIPTION/SIZE	SPECIFICATION	QTY.	UNIT PRICE	TOTAL PRICE
1.	Angle Iron	2½" x 2½" x 3/16"	---	55 ft	\$26.75/100 lbs	\$ 60.32
2.	Angle Iron	2" x 2" x ¼"	---	10 ft	\$19.75/100 lbs	\$ 6.32
3.	Angle Iron	2½" x 2½" x ¼"	---	36 ft	\$26.95/100 lbs	\$ 39.50
4.	Angle Iron	1½" x 1½" x 3/8"	---	44 ft	\$19.75/100 lbs	\$ 20.45
5.	Angle Iron	1-3/4"x1-3/4"x1/4"	---	8 ft	\$19.75/100 lbs	\$ 4.35
6.	Flat Iron Strip	2½" x ¼"	---	7 ft	\$21.95/100 lbs	\$ 3.00
7.	Flat Plate	3/4" thick	M.S. plate	1sq.ft	\$23.30/100 lbs	\$ 7.15
8.	Flat Plate	1/4" thick	M.S. plate	20sq.ft	\$24.05/100 lbs	\$ 49.06
9.	Flat Plate	3/8" thick	M.S. plate	18sq.ft	\$23.99/100 lbs	\$ 71.50
10.	Flat Plate	1/2" thick	M.S. plate	1sq.ft	\$24.90/100 lbs	\$ 5.50
11.	Ss tube	3" x 3" x ¼"	A-36	46 ft	\$ 2.60/ft	\$119.00
12.	Ss tube	4" x 4" x 3/8"	A-36	44 ft	\$ 3.45/ft	\$151.80
13.	Round Pipe	1" ID x ¼" thick	---	8 ft	\$ 1.09/ft	\$ 8.72
14.	Channel	6 U 10.5	A-36	12 ft	\$25.50/100 lbs	\$ 32.13
15.	Shaft	4" dia.	---	3½ft	\$ 1.46/lb	\$218.35
16.	Bolts & nut	½" dia. x 1½"	A-307	8	\$.23/pair	\$ 1.84
17.	Bolts & nut	5/8" dia. x 5½"	A-307 (medium carbon)	32	\$ 1.15/pair	\$ 36.80
18.	Bolts & nut	1" dia. x 5½"	A-325 (4½" shoulder)	8	\$ 1.95/pair	\$ 15.60

TABLE IV. BILL OF MATERIAL (continued)

S/NO	PART	DESCRIPTION/SIZE	SPECIFICATION	QTY.	UNIT PRICE	TOTAL PRICE
19.	Bolts & nut	5/8" dia. x 2"	A-307 (medium carbon)	12	\$.66/pair	\$ 7.92
20.	Bolts & nut	1" dia. x 7"	A-307 (medium carbon)	4	\$ 1.50/pair	\$ 6.00
21.	Bolts & nut	1" dia. x 15"	A-307 (medium carbon)	16	\$ 3.12/pair	\$ 49.92
22.	Bolts & nut	3/8" dia. x 1½"	A-307(9/16" shoulders)	16	\$.21/pair	\$ 3.36
23.	Bolts & nut	3/8" dia. x 1½"	A-307 (medium carbon)	54	\$.17/pair	\$ 9.18
24.	Lock washer	3/8" ID.	Spring washer	70	\$.04/unit	\$ 2.80
25.	Lock washer	1" ID.	TB-1632(Boston gear)	24	\$ 1.78/unit	\$ 42.72
26.	Flanged bearing	1" ID.	35689-FB-1622-14(" ")	2	\$ 3.65/unit	\$ 7.30
27.	Chain sprockets	1¼" pitch 24 teeth	100 B24 item(16572)(")	1	\$30.82/unit	\$ 30.82
28.	Chain sprockets	1¼" pitch 15 teeth	100 B15 item(15914)(")	1	\$19.02/unit	\$ 19.02
29.	Bearing	Plain cylindrical 2¼"	35366 B3644-24(" ")	1	\$10.14/unit	\$ 10.14
30.	Collar	3/4" ID.	SC 75 (Boston gear)	1	\$ 1.05/unit	\$ 2.10
31.	Collar	1½" ID	SC 150(Boston gear)	1	\$ 2.97/unit	\$ 2.97
32.	Worm	1:48 ratio	G 1114 (Boston gear)	1	\$147.78/unit	\$147.78
33.	Worm gear	1:48 ratio	L 1116 (Boston gear)	1	\$98.43/unit	\$ 98.43
34.	Worm	1:48 ratio	G 1073 (Boston gear)	1	\$30.94/unit	\$ 30.94
35.	Worm gear	1:48 ratio	L 1076 (Boston gear)	1	\$14.49/unit	\$ 14.49
36.	Pillow blocks	Plain 1½" ID	PPB 12 (Boston gear)	2	\$ 4.62/unit	\$ 9.24

S/NO	PART	DESCRIPTION/SIZE	SPECIFICATION	QTY.	UNIT PRICE	TOTAL PRICE
37.	Pillow blocks	Plain 3/4" ID	PPB 24 (Boston gear)	4	\$ 10.66	\$ 42.64
38.	Pillow blocks	3½" bore	64639-MR(Boston gear)	2	\$159.71	\$319.42
39.	Shaft	1½" dia.	M.S.	55"	\$ 55.91/100 lbs	\$ 15.46
40.	Shaft	3/4" dia.	M.S.	16"	\$ 55.91/100 lbs	\$ 1.20
41.	Hollow shaft	1½" ID x 2" OD	M.S.	9"	\$ 65.00/100 lbs	\$ 3.50
42.	Cement	---	Portland	15 ft ³	\$ 3.60/ft ³	\$ 54.00
43.	Screw jack	2" dia.jack,1/3"pitch	Acme thread, $\lambda=9^{\circ}$, M.S.	1	\$ 27.50	\$ 27.50
44.	Bolts & nut	7/8" dia. x 4" long	A-307	4	\$ 1.05/unit	\$ 4.20
45.	D.C. motor	2 hp motor 24v,60amp	Inter-harvester starter	1	\$493.50	\$493.50
46.	Freon expander	Car compressor	York	1	\$ 85.00	\$ 85.00
47.	D.C. generator	24volts - 65 amps	Mack truck generator	1	\$350.00	\$350.00
48.	Reflector	5 meter parabolic	Scientific Atlanta S.M. dish	1	\$5000.00	\$5000.00
					Sub-total	\$7742.48
	ADDITIONAL COMPONENTS TENTATIVELY SPECIFIED:					
49.	Copper piping					\$ 15.00
50.	Low alloy tubing					40.00
51.	Insulation					25.00

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